Characteristics of extremely deep reversal and Quasi-Single-Helicity (QSH) states in a low-aspect-ratio RFP

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Abstract. In a low-aspect-ratio RFP machine RELAX ($A=R/a$=0.5m/0.25m), operational regimes have been investigated over a wide range of discharge parameters. Two distinctive regimes have been identified, possibly characteristic to low aspect ratio RFP. One is very shallow reversal regime, and the other is extremely deep reversal regime where field reversal parameter lower than -1 could be sustained. The newly found extremely deep reversal regime is characterized by extremely high value of pinch parameter (>3), deep reversal parameter (<-1), with low magnetic fluctuation level. The discharge can be sustained without sawtooth crash or discrete dynamo event unlike the conventional RFPs, indicating a possible new regime of improved confinement. In shallow reversal region, SXR pin-hole images and multi-chord SXR measurements of quasi-periodic appearance of quasi-single helicity state have revealed formation of helical hot core of either a large magnetic island or helically deformed core.

1. Introduction

The reversed-field pinch (RFP) is one of the magnetic confinement systems for fusion plasma. In conventional RFPs, its configuration is self-organized and sustained by internally resonant tearing modes, which lead to magnetic chaos in the core region, unfavorable to plasma confinement. In recent years, however, two new approaches to improve the confinement properties have been demonstrated, as a result of great efforts to understand and control the self-organizing mechanism due to the tearing modes. One is current density profile control to attain the MHD-stable current profiles for suppressing the tearing instabilities [1], and the other is taking advantages of the single helicity (SH) state, where closed magnetic surfaces are recovered in a single magnetic island associated with the core resonant single dominant mode [2]. As a result, the RFP may attain a completely new view of high performance plasma confinement with weak external toroidal magnetic field.

An equilibrium analysis has shown that the aspect ratio (A) is an important parameter for optimization of the RFP because it affects the q profile or fraction of the pressure-driven bootstrap current. Optimization of the aspect ratio, including the cross-sectional shape of the plasma column, is what remains to be resolved to establish the new advanced RFP concept. Some equilibrium analyses and numerical simulations have shown that by lowering the A of the RFP, the mode rational surfaces are less densely spaced in the core region and m = 1 modes power may distribute to fewer toroidal modes, which may be helpful in attaining to the SH state. The low-aspect-ratio RFP research in RELAX has been motivated by these theoretical studies.

In this paper we will describe our new findings on the operational regimes of low-aspect-ratio (low-A) RFP plasmas in (Theta, F) space, where Theta (=Bp(a)/<Bt>) is the pinch parameter and F (=Bt(a)/<Bt>) the field reversal parameter. Extremely deep reversal discharges where F~-1 could be sustained without discrete relaxation or sawtooth event, with lowest magnetic fluctuation level. In shallow reversal regimes characterized by quasi-periodic QSH state, our new soft-X ray (SXR) diagnostics have revealed formation of helical hot core in such discharges. Characterization of RFP discharges will be described in these two regimes.

2. Description of RELAX machine

RELAX ($A=R/a=0.5$m/0.25m) is a low-A RFP machine to explore the potential advantages of low-A configurations [3]. We have used a 4-mm thick SS vacuum vessel with major radius R of 0.51 m and minor radius a of 0.25 m with $A=2$, the lowest-A RFP machine to date. The vessel has two poloidal gaps but no toroidal gap; The field penetration time is about 1.5 ms, much shorter than in other resistive wall RFPs. No conducting shell has been attached, with the aim at active control of MHD instabilities by means of external magnetic fields in low-A RFP configuration. RELAX is equipped with two toroidal arrays of 14 magnetic probes inserted from top and bottom ports equally spaced toroidally with toroidal separation angle of 22.5 degrees, except at two poloidal gap locations. Each probe measures toroidal and poloidal fields. The difference of the top and bottom signals provides the odd components of the edge magnetic fluctuations, while the sum, the even components. RELAX is also equipped with a poloidal array of 6 magnetic probes each of which measures the edge toroidal field. A radial array of 13 magnetic probes is used to measure the radial profiles of B_r, B_θ and B_ϕ at $0.6<r/a<1.0$. In addition, toroidal arrays of toroidal flux loops, sine and cosine coils for B_r measurement outside the vessel, are attached on the outer surface of the vessel. All these pick-up coil signals are sampled at a frequency of 2 MHz and then numerically integrated. After the integration, we use a 0.5-kHz or 2-kHz high-pass filter to obtain the fluctuating component.

The discharge and plasma parameters in RELAX attained to date are as follows: plasma current Ip of up to 100kA, discharge duration of up to 2.5ms, electron density in the range from 0.1 to 2.0 times10^{19} m^{-3} from millimeter-wave interferometry [4], and electron temperature <100eV from double–filtered soft-X ray (SXR) measurements. Further studies to improve the RFP plasma performance are in progress. In low-A RELAX plasmas, the configuration tends to relax to a quasi-single helicity (QSH) state in which the internally resonant single tearing mode grows significantly larger than the other modes. A high-speed camera diagnostic has revealed a simple helix structure in visible light images [5]. In the extreme case, a rotating helical Ohmic equilibrium (HOE) state has been realized [6]. Recent development of a SXR pin-hole camera for tangential images of low-A RFP plasmas have revealed formation of helical hot core in QSH state [7].

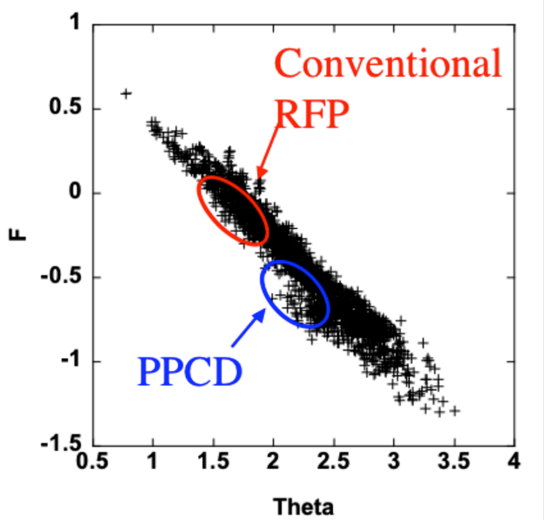

Fig.1. Discharge regimes of RELAX in (Theta, F)

3. Characterization of RELAX Plasmas

3.1. Characterization of Discharge of Low-A RFP

The RFP configuration is often discussed in (Theta, F) space. Figure 1 shows the (Theta, F) regions attained in RELAX. Each point represents a time averaged value over 0.5 ms in the current flat-topped phase, which is defined as the time period where time change in plasma current over 0.5ms is lower than 5% including the maximum plasma current. In conventional RFPs, typical operational region lies in the ranges 1.4<Theta<2, and -0.5<*F*<-0.1. In the improved confinement regime like PPCD or improved high-Theta mode in TPE-1RM20 [8], the region extends to higher-Theta and deeper-*F* region. These two regions in conventional RFPs are indicated in the figure for the reference. It is clear from Fig.1 that in RELAX discharges, extremely high-Theta, deep-*F* regions can be attained. without significant disruptive phenomena such as sawtooth crash or discrete dynamo event.

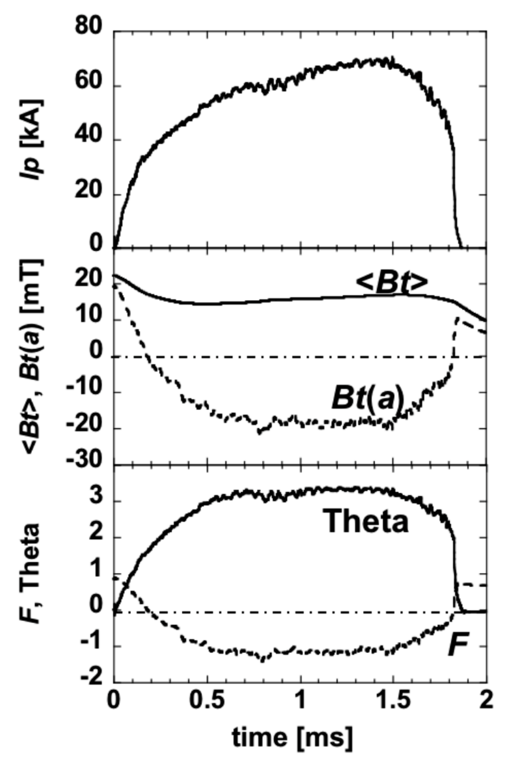

Fig.2. Time evolution of Ip, <Bt>, Bt(a)*, Theta and* F *in deep reversal discharge.*

Figure 2 shows an example of a discharge in the regime characteristic to RELAX where Theta~3 with *F*< -1.0. The extremely deep-*F* state has been maintained for ~1ms without significant disruptive phenomena such as sawtooth crash or discrete dynamo event. The *q* profile reconstructed for this type of discharge using the RELAXFit code [9] shows strong magnetic shear in the outer region, which may contribute to attainment of the extremely high-Theta and deep-*F* regions without sawtooth crash. In deep reversal discharges, the magnetic fluctuation amplitudes decrease with broader spectrum. The increased magnetic shear may result in lower mode amplitudes in extremely deep reversal regime.

3.2. Behavior of magnetic fluctuations of Low-*A* RFP

In Fig.3, we compare the toroidal mode spectra of m=1 and m=0 modes together with *q* profiles reconstructed using the RELAXFit code [9]. The spectral analyses have been carried out using the magnetic fluctuation data in the current flat-topped phase for 0.5ms. In Fig.3(a), the RFP discharge is characterized by very shallow reversal and high level of magnetic fluctuations. The innermost resonant surface is for m=1/n=4 mode, and the field reversal surface is located close to the wall. In the shallow-reversal regime, the discharge is characterized by quasi-periodic appearance of quasi-single

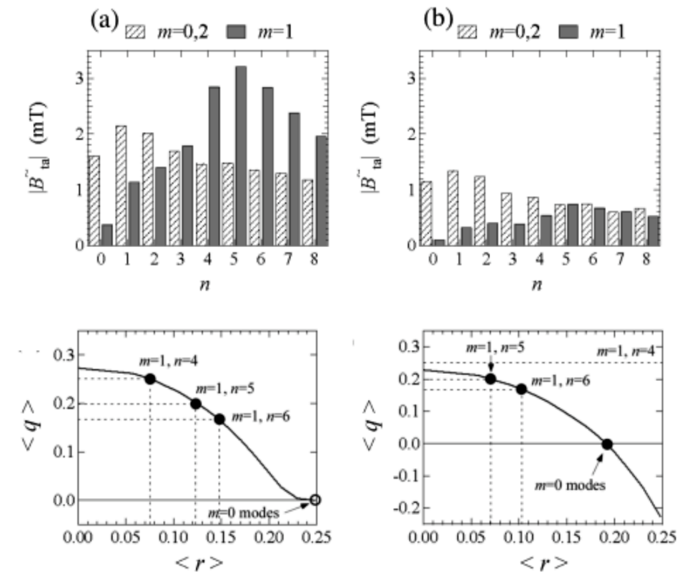

Fig.3. Troidal mode spectra of even and odd components in (a) shallow and (b) deep reversal plasma. The q-profiles are sketched as below.

helicity (QSH) state, and the magnetic fluctuation spectrum is dominated by m=1/n=4, 5 modes with large amplitudes [10]. In the extreme case, internal magnetic field measurement shows the helical Ohmic equilibrium (HOE) configuration [6]. The importance of low-*A* configuration is that the QSH or HOE can be achieved in low current density without magnetic boundary control. In Fig.3(b), the discharge is characterized by deep reversal, where the field reversal parameter *F* (= edge toroidal field normalized to average toroidal field) decreases to ~-1. In deep reversal discharges, the innermost resonant surface is for m=1/n=5 mode, and the field reversal surface is located far from the wall. The magnetic fluctuation amplitudes decrease and spectrum with a broad peak at the innermost resonant m=1/n=5 mode, showing the characteristic of multi-helicity (MH) RFP state.

4. Helically structure in very shallow reversal region

The toroidal mode spectrum is narrowed by reducing the toroidal field reversal, and the QSH state is realized in shallow reversal discharges [10]. In order to study the plasma structure in very shallow reversal region, we have taken SXR tangential images using a SXR pin-hole camera with a 2-micrometer aluminum filter. The experimental arrangement is shown in Fig.4(a). The SXR imaging diagnostic system consists of a pin-hole camera and an ICCD camera to obtain high time resolution. Figure 4(b) shows an experimental SXR image with 5-micro sec exposure during a single m=1/n=4 mode dominated period. This experimental image was compared with a simulated image in Fig.4(c) which was obtained as follows. The SXR emissivity in the background plasma was assumed to be Gaussian in shape, with FWHM of 17.5cm (0.7*a*). The SXR image on the MCP was calculated with by assuming a bean-shaped m=1/n=4 magnetic island at $r_{s\_n=4}$=14cm with the normalized width of 12%. The SXR emissivity inside the island was assumed twice as high as that in the background (at the O-point). The helix similar to the experimental result was reproduced in the calculated image. In Fig.4(d) and (e), we have compared the vertical profiles of the brightness of the experimental and calculated images. In Fig.4(d), the vertical profiles of the brightness in the experimental image at X_p=0 (along the central vertical chord) is compared with the similar calculated profile at X_p=-0.2, where X_p is the normalized horizontal coordinate on the MCP surface. The reason for comparison at different radial locations is to test the effect of the Shafranov shift, which is estimated to be about 0.2*a* from equilibrium reconstruction using the RELAXFit code, but not taken into account in calculating the tangential images. Aside from the experimental peak at Z_p~-0.55 and slight discrepancy in the region Z_p>~0.6, the experimental and calculated profiles agree well. In Fig.4(e), similar comparison has been made at X_p=0.3 for the experimental and at X_p=0.1 for the calculated images. In this case, there arises a discrepancy in the peak position, however, the overall characteristics

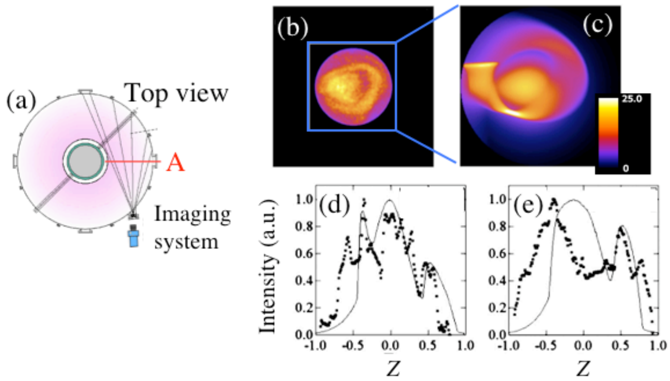

Fig.4. (a) Arrangement of the SXR pin-hole camera. (b) An experimental SXR image. (c) A simulated SX image for a single island model. (d) Contour of model SXR emission intensity in the poroidal cross section A in (a). (e, f) Horizontal(X) and vertical(Z) intensity profiles in the SXR images. The solid lines are for the experimental, and the circles are for the simulated profiles.

show good agreement. From the results in Fig.4(d) and (e), we may conclude that the major features of the experimental tangential SXR image could be reproduced by a single island model. It is clear that we need further effort to adjust the island parameters to realize better agreement between the experimental and calculated images. The small-scale structures seen in the experimental images (dotted lines in Fig.4(d) and (e)) may represent the effect of the neighboring modes, which might also have island structures.

We have carried out magnetic field line trace for the helical Ohmic equilibrium discharges using ORBIT code [11]. As shown in Fig.5 (a), the 1-D equilibrium simulating the very shallow reversal profile was given, and the Newcomb equation was solved to obtain radial eigen-function of the m=1 magnetic field perturbation. The amplitude of the mode was determined so that it matches the edge measurement. The modes taken into account and their amplitudes were based on the experimental toroidal mode spectrum in QSH phase, as shown in the figure 5(b). The field line trace was carried out by calculating the particle orbit with has only the parallel velocity, and the Poincare plot was produced in a poloidal cross section to see the structure of magnetic surfaces. As shown in the figure 5(c), we can identify the closed helical magnetic surfaces inside which closed magnetic surfaces are formed, with possible remaining of the original axisymmetric magnetic axis. It should be noted that in the present analysis we have used the ORBIT code, which is based on 1-D model equilibrium and 1-D Newcomb equation solver in a cylindrical model. The results in Fig.5 may not apply directly to the RELAX experiment, however, we may conclude that the results from field line trace using the ORBIT code are consistent with the SXR imaging diagnostics in that the helical structure is formed in the core region in very shallow discharges in RELAX.

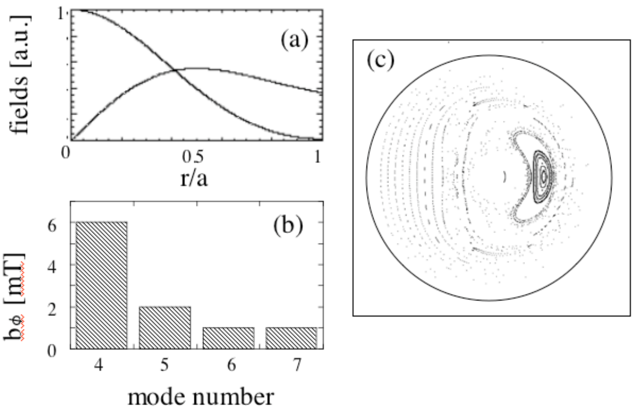

Fig.5. (a) The 1-D equilibrium simulating the very shallow reversal profile. (b) The modes taken into account and their amplitudes were based on the experimental toroidal mode spectrum in QSH phase. (c) Reconstructed magnetic surface.

Figure 6 shows the SXR emission profile measured with a multi-chord photo-diode array. The SCR emission is almost centrally peaked, and strong increase in SXR during flat-topped plasma current phase is observed. When we look at the behavior of contours of SXR emission intensity during a current flat-top phase, the intensity oscillates at a frequency of ~10kHz, and we may be able to identify a change in the peak position in time. The linear

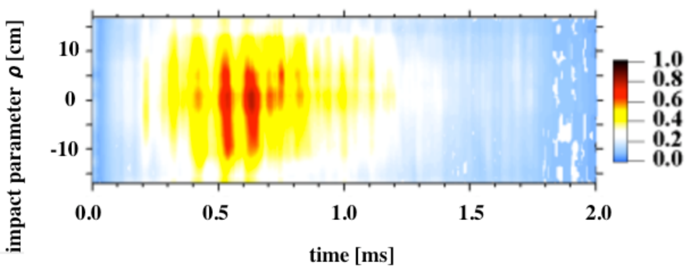

Fig.6. Time evolution of SXR profile obtained from multi-code photo-diode.

change in the peak position with time in the contour plot may indicate toroidal or poloidal rotation of the helical hot region, which is consistent with the results from SXR imaging diagnostic. We need further studies to improve the spatial resolution in peak may indicate rotation of helical structure in SXR emission. These results also suggest an existence of helically deformed hot core. In RELAX plasmas where a single mode dominates magnetic fluctuation, the results have clearly shown that there exist high-density, high temperature core region with simple helical structure.

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5. Summary

We have described two distinctive discharge regimes characteristic to low-A RFP configuration, that is, regions, i.e., newly found extremely deep reversal region, and very shallow reversal region. The extremely deep reversal region In RELAX is much deeper reversal than in the conventional RFP machines in which deep reversal regime can be attained either by active control of plasma current profile like PPCD in MST or careful wall conditioning to suppress impurity influx for excess shrink of plasma current channel to keep the stability to kink modes in TPE-1RM15. The magnetic fluctuation level decreases with deepening the field reversal, and the SXR emission intensity increases in the extremely deep reversal region. This newly found region may have a potential to improved confinement in the RFP. In the very shallow reversal regime, new SXR diagnostics have revealed the existence of helical hot core in QSH discharges. We need further elaboration of the imaging diagnostics to identify whether the shape of the helical structure is magnetic island or helically deformed 3-D magnetic axis configuration. We may note that the radial profile measurements of the magnetic fluctuations suggest the latter case.

Acknowledgment

This work as supported by a Grant-in-Aid for Scientific Research (No.17360441) from Ministry of Education, Culture, Sports, Science and Technology of Japan, and partly by a National Institute for Fusion Science (NIFS) Collaboration Program No. NIFS07KOAH022.

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